III.E.7 Low-Cost/High-Temperature Heat Exchanger for SOFCs Using Near-Net-Shape Ceramic Powder Forming Process

Objectives

- Design a counter flow heat exchanger for cathode preheat of solid oxide fuel cells.
- Develop a computational model to accurately predict the effectiveness of heat exchangers.
- Demonstrate a process of forming ceramic composite heat exchangers using rapid prototype tooling and a proprietary near-net-shape powder forming process.
- Optimize the heat exchangers for high effectiveness and low pressure drop using computational fluid dynamic (CFD) simulation.
- Validate the CFD simulations with experimental data collected from the heat exchangers under actual operating conditions.

Accomplishments

- Designed, fabricated, and validated experimentally to within 3% a 62% effective, computationally modeled heat exchanger operating at 900°C and a 5 kW flow rating.
- Designed an 83% effective computational heat exchanger model.
- Manufactured a 15 cm x 35 cm one-piece complex Si-SiC prototype using rapid prototype tooling and a near net shape forming process (see Figure 1).
- Tested a 73% effective 15 cm x 55 cm one-piece prototype at 980°C and a 5 kW flow rating.
- Developed a methodology for accurately modeling and simulating the effects of geometry changes computationally to achieve an effectiveness between 70% and 90% while maintaining a pressure drop of less than 10” w.c.

Tom Briselden (Primary Contact), Christopher Wyant, Nathan Lang
Spinworks, LLC.
5451 Merwin Lane
Suite 207
Erie, PA 16510
Phone: (814) 899-4871; Fax: (814) 314-0288
Website: www.spin-works.com

DOE Project Manager: Magda Rivera
Phone: (304) 285-1359
E-mail: Magda.Rivera@netl.doe.gov

Subcontractors:
Penn State Erie, School of Engineering and Engineering Technology, Erie, Pennsylvania

Introduction

Without a low-cost high-temperature heat exchanger, the solid oxide fuel cell system (SOFC) may not meet the electric conversion efficiency goal of 60% and installation cost of $400/kW. Because it operates at temperatures near 750°C, exhaust gases exceeding this temperature may remove a substantial amount of the energy supplied to the fuel cell. Capturing this high quality energy and preheating the fuel cell's cathode air is a promising method to improve SOFC efficiency.

One method of capturing high quality energy is through the use of heat exchangers. Traditional alloy-

FIGURE 1. Prototype Heat Exchanger

based and ceramic heat exchangers have a prohibitive life cycle cost impact on the SOFC due to high initial costs and material limitations such as creep, thermal shock, and sulfidation attack. An opportunity exists for a low-cost, high-temperature cathode air SOFC heat exchanger that can operate under the following challenging conditions:

- 750°C to 1,000°C
- 11.7 kg air/kW hr
- 32°C/cm temperature gradient
- 50 ppm sulfur
- 70% to 90% effectiveness
- < 5" w.c. pressure drop on the hot side
- < 10" w.c. pressure drop on the cold side
- Withstand over 2,000 thermal cycles from ambient temperature to maximum operating temperature
- 40,000 hours life
- 10,000-hour maintenance interval
- Minimal Si or Cr carryover to eliminate membrane contamination
- < 10% impact on the overall installation cost of the SOFC

Approach

The approach taken was to develop a system in which a heat exchanger can be optimized for any SECA member's specifications, the necessary tooling rapid prototyped from that optimized shape, and finally the heat exchanger formed and tested under actual operating conditions. This system allows full mass customization of the heat exchangers while keeping the forming and firing process essentially the same for manufacturing.

A commercially available, low-cost Si-SiC material was used to manufacture a highly effective (between 70% to 90%) heat exhanger. The material has a proven life history greater than 100,000 hours in high temperature natural gas and air environments with severe thermal shock. Minimal Si carryover into the fuel cell membrane is estimated. Complex helical shaped heat exchangers were designed in three dimensions and computationally modeled. A rapid prototype tool was used to facilitate a near-net-shape, patented, ceramic powder formed, one-piece component. It is estimated that the one-piece method will result in a low-cost (< 10% of SOFC system cost), high-temperature heat exchanger with a life expectancy that meets the goals of SECA members.

Results

The first step of this process was to validate the computational analysis. To accomplish this, simulations of four simple counter-flow heat exchangers were analyzed computationally. At the same time, the four heat exchangers were manufactured and tested experimentally. The initial flow and wall surface characteristics were set as a result of these four simple heat exchanger tests. These flow and wall characteristics were then used as the inputs into all successive simulations.

A computational study was then conducted to determine the change in effectiveness that varying the inlet conditions and the geometry of the heat exchangers (including the number of flow channels, the twist rate, and differing mass flow rates) would have (see Figure 2). The end result of this study was a 50% effective heat exchanger that fits the SECA inlet and pressure drop requirements.

A theoretical analysis was then performed to optimize each flow channel in the heat exchanger. The optimization was done in regards to a heat transfer "Figure of Merit" (maximizing the surface heat transfer coefficient for a given pressure drop). This resulted in a 12% increase in effectiveness with no additional pressure drop in the same size heat exchanger.

The tooling required to manufacture this 62% effective heat exchanger was then rapid prototyped and the heat exchanger was manufactured. The testing on the heat exchanger was performed on a 5 kW heat exchanger test rig developed in house. This test rig simulates the effluents coming off of a 2.5 to 6.25 kW fuel cell in operation. The mass flow rate and temperature of the effluents, as well as the incoming preheat air, are monitored and controlled. The pressure drop and outlet temperature of each channel can also be monitored. The computational results, using the flow and wall characteristics developed in the validation

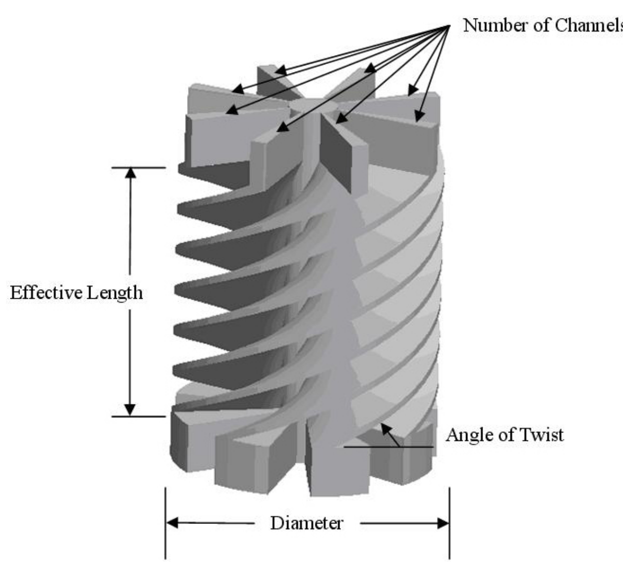

FIGURE 2. Heat Exchanger Geometry

stage of the project, were validated to within 3% in effectiveness (59% effective in experiment). Further simulations and tests were performed using mass flow rates simulating effluents from 2.5 to 6.25 kW fuel cells at 800°C and one special case which was a 3.0 kW equivalent operating at 725°C. This data was then used to validate the CFD simulations (see Figure 3).

Upon proving that the computational analysis accurately predicts the effectiveness of the heat exchangers with varying geometries and inlet conditions, heat exchangers have been computationally designed with an effectiveness range as high as 83%; however, these heat exchangers were outside the current manufacturing capabilities. Concurrently, heat exchangers were formed, fired, and tested for 5 kW fuel cells with as high as 73% effectiveness and at inlet temperatures as high as 980°C.

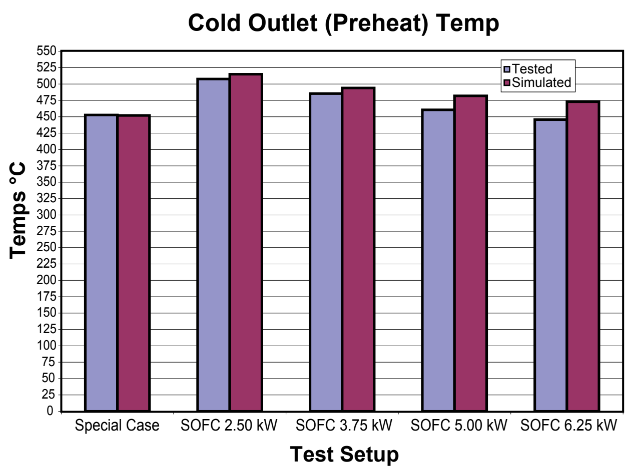

FIGURE 3. Preheat Temperature Comparison

Conclusions and Future Directions

By using a patented near-net-shape ceramic powder forming process and supplementing it with the ability to fully optimize the design for any inlet conditions and any operating constraints (size, pressure drop, manifolding, etc.) and easily prototype the tooling required for forming, fully functional and optimized heat exchangers can be produced for costs within the SECA requirements.

The future plans for this project are to:

- Using computational analysis, identify the key variables that maximize effectiveness and minimize component volume for a 3 kW to 10 kW SOFC helical fluent channel heat exchanger.
- Using advanced 3-D modeling, rapid prototyping, and near-net-shape powder forming, design and manufacture one-piece helical fluent channel prototypes with an effectiveness between 70% and 90%.
- Test the prototypes under simulated SOFC conditions between 650°C to 1,000°C to validate performance and manufacturing integrity.
- Utilizing input from SECA members, market data, and the performance map, design custom ThermCor™ prototypes and ceramic and ceramic/metallic manifolds to interface with SOFC systems.
- Using the HeatCor™-Industrial pilot manufacturing plant (11,000 units/year at $400/unit-5 kW) as a benchmark, implement design for manufacturing build to order, mass customization, and other key technical upgrades to design a 50,000 unit/year plant to produce a $250/unit, 5 kW heat exchanger.
- Produce and test “commercial ThermCor™ prototypes” for SOFC systems.